Analysis of the Utility of NOAA-Generated Tropospheric Refraction Corrections for the Next Generation Nationwide DGPS Service

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BIOGRAPHIES

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David Dodd has been involved in surveying for the last 24 years. He received a B.Sc. (1987) and an M.Sc (1994), in Surveying Engineering from the University of New Brunswick in Fredericton, NB, Canada. Dave is currently the coordinator of the Hydrographic Program at the University of Southern Mississippi, and enrolled in the doctoral program.

Allen Cleveland served more than 28 years in the U.S. Coast Guard. His accomplishments include redesign of Coast Guard communication station transmit control systems and design and fabrication of the first multi-mode and multi-agency mobile communications facility. He was managing lead engineer for the Coast Guard's next generation tactical and navigational system and is currently employed at C2CEN assigned as lead reference station and integrity monitor architecture engineer.

LT Michael Parsons is a 22-year Coast Guard radio navigation veteran. He recently completed service as the Western DGPS Operations Control Station Manager, where he supervised operation of remotely located DGPS sites in the Western United States, Alaska, and Hawaii. He is currently the DGPS hardware section chief at the Coast Guard Command and Control Engineering Center (C2CEN) in Portsmouth, VA.

ABSTRACT

The U.S. Coast Guard has begun the modernization of its Nationwide Differential GPS (NDGPS) beacon network. One potential component of modernization is the transmission of not only pseudorange corrections but also pseudorange and carrier phase measurements from reference stations. Such an augmentation could provide for long baseline, centimeter-level, differential carrier phase processing.

In order to achieve precise, long baseline results, improved handling of atmospheric refraction of the incoming GPS signals must be achieved. Assuming ionospheric-free data processing, the modeling of tropospheric delay becomes the limiting factor. The Forecast Systems Laboratory at the National Oceanic and Atmospheric Administration (NOAA) has developed an experimental tropospheric delay product within the continental U.S. (CONUS). The purpose of this paper is to analyze the accuracy of the NOAA tropospheric product and quantify its usefulness in GPS data processing.

The accuracy of the NOAA tropospheric delays was determined by comparison against GPS estimated delays from the International GPS Service (IGS) and from existing tropospheric delay models. The NOAA zenith total tropospheric delay r.m.s. difference ranged from 15 to 25 mm. The WAAS model comparison r.m.s. values were larger and the Saastamoinen and Hopfield models even larger. As expected, these latter three models showed significant station-dependent variation. The utility of the NOAA tropospheric delays in position determination was accomplished by supplying the NOAA zenith delay estimates to an in-house ionospheric-free relative GPS processor. Results indicate that the most significant improvement is observed in up-component bias reduction of a few centimeters to more than a decimeter.

Follow-on work involves processing more varied data sets; refining current GPS data processing; suggesting methods of disseminating the NOAA corrections; and performing a similar analysis with experimental ionospheric products.

INTRODUCTION

The U.S. Coast Guard in cooperation with other federal agencies, including the Department of Transportation and the Federal Railroads Administration has begun the modernization of its highly successful Nationwide Differential GPS (NDGPS) beacon network. Aside from simply replacing aging equipment, the modernization program calls for investigations into improving the quality of the service in terms of integrity, availability, precision and accuracy. One of the most interesting options is transitioning from transmitting not only pseudorange corrections but also pseudorange and carrier phase measurements from NDGPS reference stations. Such an augmentation could provide for long baseline, few centimeter-level, differential carrier phase processing, resulting in numerous new or improved positioning and navigation applications tens-to-hundreds of kilometers from Coast Guard transmitters.

In order to achieve precise, long baseline results, *e.g.*, double-differenced, integer cycle carrier phase solutions, improved handling of atmospheric refraction of the incoming GPS signals must be achieved. The Space Environment Center, National Geodetic Survey, and Forecast Systems Laboratory at the National Oceanic and Atmospheric Administration (NOAA) have developed experimental ionospheric and tropospheric delay products within the continental U.S. These products are based on enormous amounts of NOAA data and novel inversion techniques. A consequence of these products is that in GPS data processing, atmospheric error terms may be estimated by non-GPS means, allowing the GPS measurement strength to be retained for position estimation.

As an initial study, the Hydrographic Science Research Center at the University of Southern Mississippi is working with the Coast Guard to analyze the utility of the tropospheric delay product in support of the following overall goals: to characterize the quality of the NOAA tropospheric delay correctors; to estimate the effects on positioning by applying the correctors to GPS data processing; and to provide options for ingesting these correctors in the NDGPS modernization program.

The quality of the NOAA correctors was determined by comparing the NOAA tropospheric delays against GPS estimated delays from the International GPS Service (IGS) and from existing closed-form tropospheric delay models. The mapping of the effectiveness of the NOAA tropospheric delays from the range to position domain was performed by applying the correctors to differential carrier phase processing. Such an approach has recently shown promise [Jensen, 2002].

MODEL EVALUATION METHODOLOGY

The NOAA model evaluation consists of two analysis components: first, accuracy of delay estimation in the range domain; and second, effect of application of delay estimation in positioning solutions. NOAA delay estimate comparisons were performed against other tropospheric delay estimators.

IGS Tropospheric Estimates: Reference Solution

In order to assess the accuracy of the NOAA model, which in theory should be superior to closed-form models, we turned to GPS-based estimates of total zenith path delay from IGS stations. Essentially, GPS processing is performed with data from geodetic receivers at known locations to estimate a total zenith path delay from mapped GPS satellite slant paths. Solutions from various IGS Analysis Centers (globally distributed governmental and academic institutions) are combined to construct a number of products, including the final troposphere product. This data type contains total zenith path delay at a sub-set of IGS stations, produced at a two hour interval, with an approximately two week latency. The IGS [2004] estimates that the accuracy of this product is a few mm (1σ). One limitation of this approach is the limited number of IGS stations in CONUS. Figure 1 illustrates this point with a diagram of all stations in North America. A large gap can be seen in the U.S. southeast. This limitation is exacerbated by the fact that tropospheric delays are estimated at only a subset of these sites.

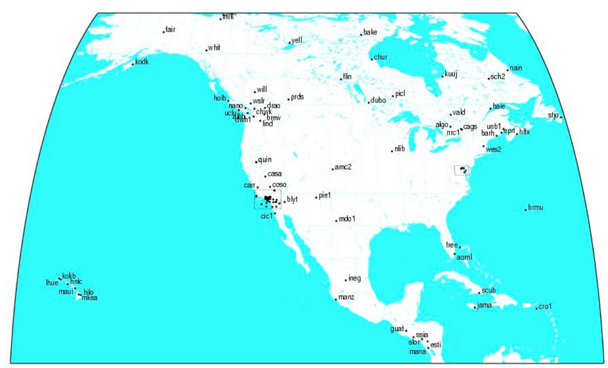

Figure 1: IGS station distribution in North America [IGS, 2004].

NOAA Tropospheric Model

The NOAA tropospheric delay model was developed by the Forecast Systems Lab at NOAA [Gutman *et al.*, 2003]. The model consists of a numerical weather prediction model in which GPS zenith delay data are assimilated. The GPS data are collected from a large subset of Continuously Operating Reference System (CORS) sites. One manner in which to view this technique is that it allows for the GPS data to constrain the integrated delay in the weather model, while the weather model provides a physics-based method of interpolating and extrapolating delays in space and time.

The processing flow of delay calculations is given in Figure 2. The inputs are: latitude, longitude, ellipsoid height, and time, and the outputs are: zenith hydrostatic delay and zenith wet delay for the current time (last assimilation) and for a two-hour prediction. Note that the two-hour prediction values are used in the analysis to come. The estimation is currently realized in a suite of client software consisting of C, FORTRAN, and Perl programs, which access NOAA tropospheric grid files via FTP. These grids are produced hourly, with ~20 km grid spacing. The grids contain nowcasts and two hour forecasts. Further information can be found at http://www.gpsmet.noaa.gov.

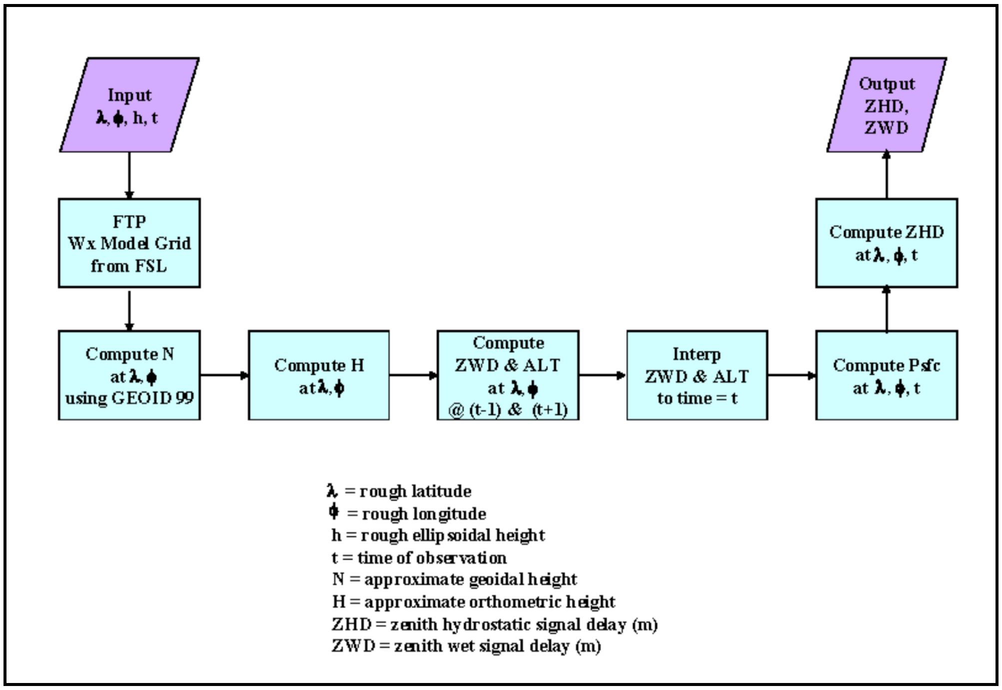

Figure 2: NOAA tropospheric delay processing flowchart [Gutman *et al.*, 2003].

Conventional Closed-Form Tropospheric Models

Given that many GPS processing packages use conventional tropospheric models, two popular ones were also included in the analysis: the Hopfield model [Hopfield, 1971] and the Saastamoinen model [Saastamoinen, 1973]. The Hopfield model is a function of temperature, pressure, water vapor pressure, and orthometric height, while the Saastamoinen model is a function of temperature, pressure, water vapor pressure, orthometric height, and latitude. However, surface meteorological input is typically not available during GPS receiver operation, so standard values were used along with height and latitude (for Saastamoinen). Note that the Neill wet and hydrostatic mapping functions [Neill, 1996] were also used to project the IGS and NOAA zenith delays to slant.

WAAS Tropospheric Models

The Wide Area Augmentation System (WAAS) model was developed for aviation applications, but has found favor in the broader community. It is essentially the Saastamoinen zenith delay model, with surface meteorological input provided by a lookup table [Collins, 1999]. The table is based on U.S. Standard Atmosphere Supplements of 1966. The overall model is still closed-form, but is a function of only latitude, orthometric height, and day of year. Unlike the other models, the simple Black and Eisner mapping function [Black and Eisner, 1984] is used to reduce computation burden.

RANGE DOMAIN ANALYSIS

The spatiotemporal nature of the tropospheric delay can best be observed from images of the estimated delay. The NOAA product is provided in a convenient grid form of wet delay and atmospheric pressure. And given the fact that though wet delay represents only approximately 10% of the total delay – it represents most of the unmodeled error (correct height and pressure information allows for very good estimation of hydrostatic delay), maps of the NOAA wet delay are very revealing. Four such images for 25 May 2004 are presented in Figure 3, separated by six hours in time. A correlation between tropospheric delay and topography exists, as the delays are computed from the terrain – the lower the altitude of the location, the more tropospheric delay observed. Given the observed spatial and temporal variations, delay models that do not include actual surface meteorological measurements cannot realistically estimate wet delay. And even if surface measurements are available, they do not necessarily represent the behavior of these constituents throughout the vertical atmospheric profile. In areas of similar altitudes, such as the southeast, it is clear that the delays do not remain constant along lines of latitude. The movement of water vapor in weather fronts is also seen. As observed by Gregorius and Blewitt [1998] and others, such fronts have an adverse impact on tropospheric modeling in GPS. In summary, assuming that the NOAA wet delay estimates are realistic (which will be determined later in this section), it is very unlikely that any existing closed-form model will be able to accurately predicted wet tropospheric delay for any location, the majority of the time.

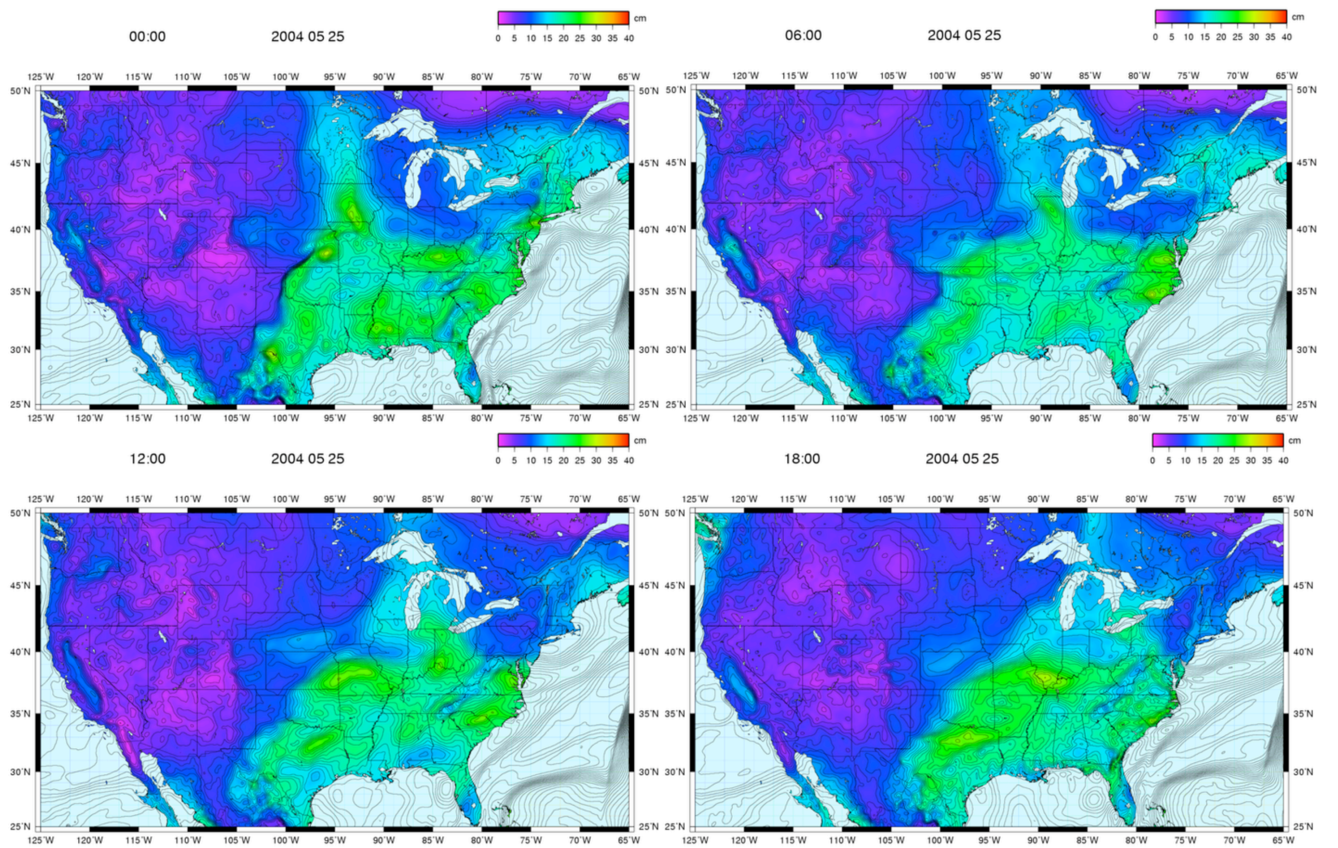

Figure 3: NOAA zenith wet tropospheric delay maps of CONUS for UTC hours 0, 6, 12, and 18 on 25 May 2004.

To further illustrate the spatiotemporal decorrelation of wet delay, Figure 4 contains images of NOAA differential zenith wet delay with respect to New Orleans. There is little height change in this region, so most differential delay is due almost completely to the wet component. The circles represent 100 km radii from New Orleans. Two observations are worth noting. One, even with zenith differential delays, the presence of water vapor masses is noticeable. And two, following along a circle of proximity, the differential zenith delay can vary from 0 to over 10 cm. Therefore, a strict directly proportional relationship between increasing GPS baseline length and increasing differential tropospheric error represents an oversimplification.

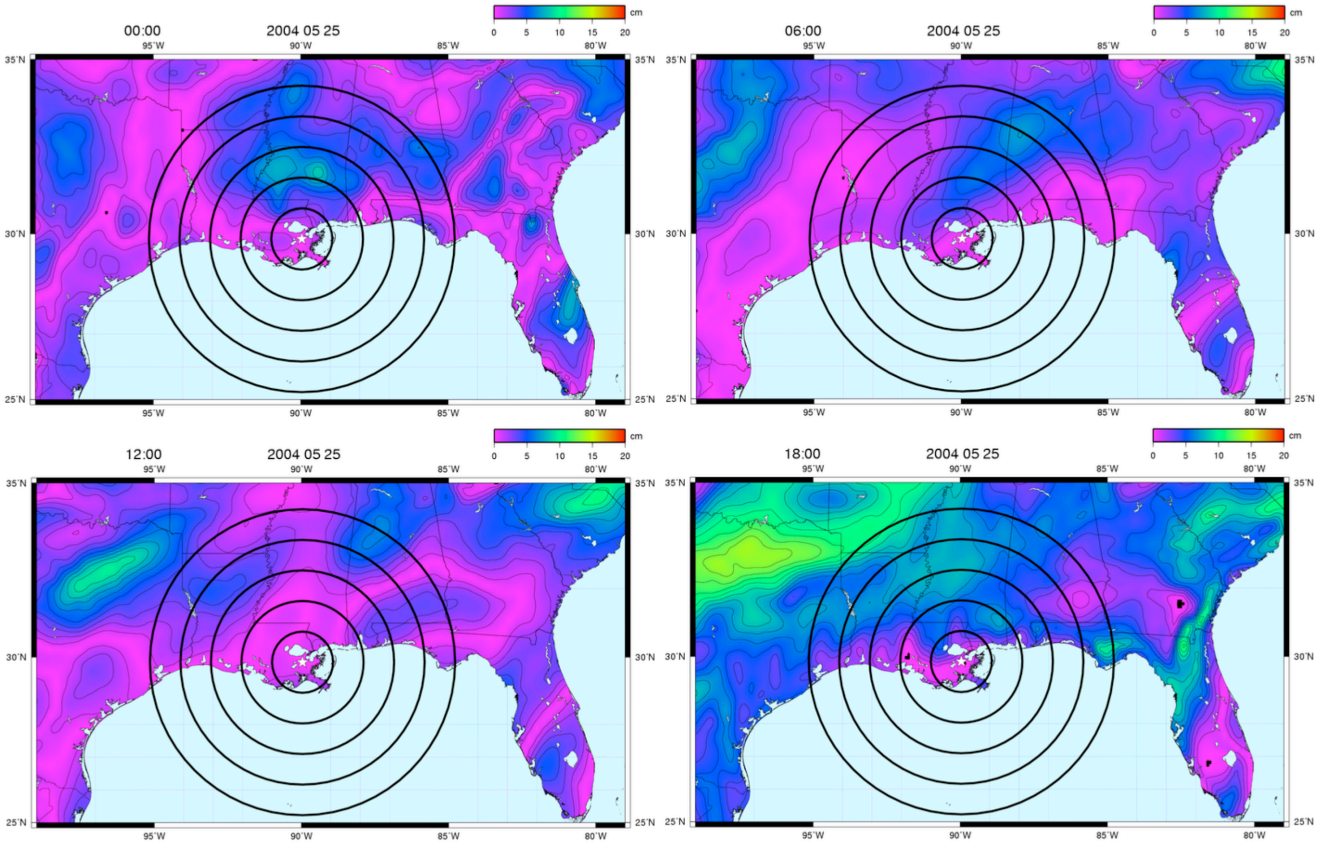

Figure 4: NOAA differential zenith wet tropospheric delay maps of the U.S. southeast for UTC hours 0, 6, 12, and 18 on 25 May 2004. Differences are with respect to New Orleans. (Each circle represents an additional 100 km radius from the center.)

To determine the accuracy of the NOAA product, a practical reference or "truth" solution must first be identified. As discussed, the IGS final tropospheric delay product has been selected. Figure 5 illustrates the zenith total delay for station DWH1 in Washington state for approximately three months, at 2 hour intervals, in mid-2004. The location of DWH1 is: 238 °E, 48 °N, 109 m (ellipsoidal height). The mean estimated precision for the delays (as determined by the IGS) is 1.8 mm. The variability in the total delay is rather striking.

Figure 6 illustrates the estimates of zenith total delay from all five products and models over the three month period. The NOAA product tracks the IGS product very well. The WAAS model follows the general trend of the two products with a bias. The smooth nature of the WAAS time series is a function of the averaging of its input historical meteorological data. The Saastamoinen and Hopfield models produce almost identical results. Both time series are represented by straight lines, as station DWH1 is stationary and no surface meteorological data were utilized.

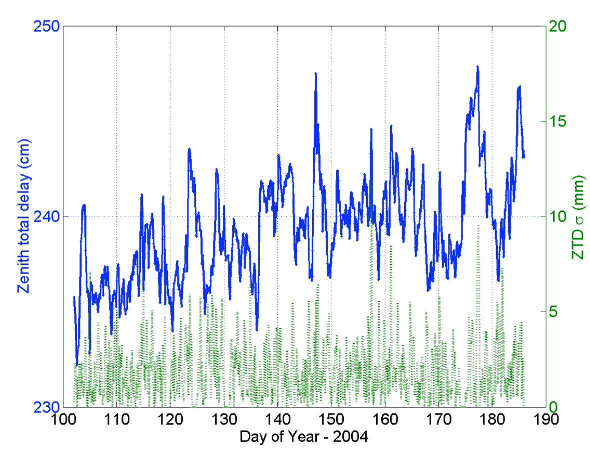

Figure 5: IGS final tropospheric delay estimates over ~3 month period for station DWH1 in Washington state.

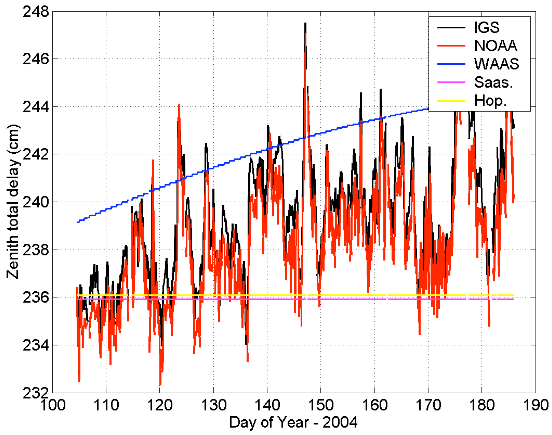

Figure 6: IGS, NOAA, WAAS, Saastamoinen, and Hopfield tropospheric delay estimates over ~3 month period for station DWH1 in Washington state.

The differences between all the models with respect to the reference IGS estimates is given in Figure 7. It is quiet obvious that the NOAA estimates follow the IGS estimates with little bias (10 mm) and low magnitude, high frequency noise. The r.m.s. difference is 13 mm. The r.m.s. for the WAAS estimates is 36 mm, while the r.m.s. for the Saastamoinen and Hopfield estimates is 41 mm.

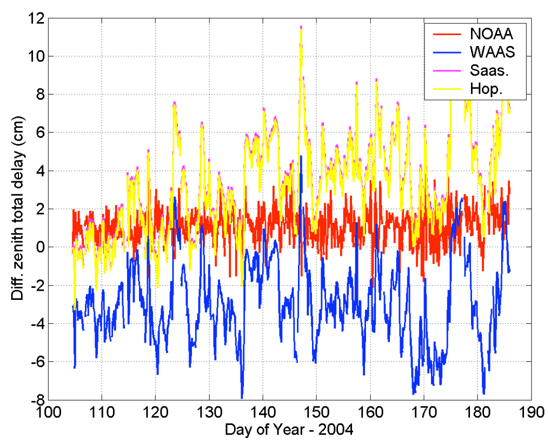

Figure 7: NOAA, WAAS, Saastamoinen, and Hopfield tropospheric delay estimates as compared to IGS estimates over ~3 month period for station DWH1 in Washington state.

Figures 8, 9 and 10 show the effect of differencing between the IGS and NOAA, WAAS, and Saastamoinen estimates, respectively, as mapped to slant delay with mapping functions. (Note that the same scale is used for all three plots. And the elevation angle ranges from 90° to 20°, since presenting to, *e.g.*, 5° would mask the structure at the higher elevation angles.) As is well know, the difference increases as elevation angle decreases. The NOAA results are relatively smooth, since the zenith delay differences are small and the mapping functions used are the same as those for the IGS estimates.

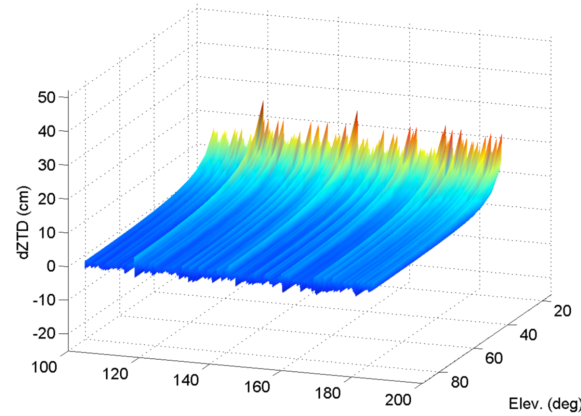

Figure 8: NOAA tropospheric delay estimates mapped to elevation as compared to IGS estimates over ~3 month period for station DWH1 in Washington state.

The WAAS-based differences (Figure 9) are larger throughout the elevation range. However at lower angles the structure changes from that of the NOAA figure, because unlike NOAA and the IGS that have been projected using the Neill mapping functions, WAAS uses the much less complex Black and Eisner mapping function.

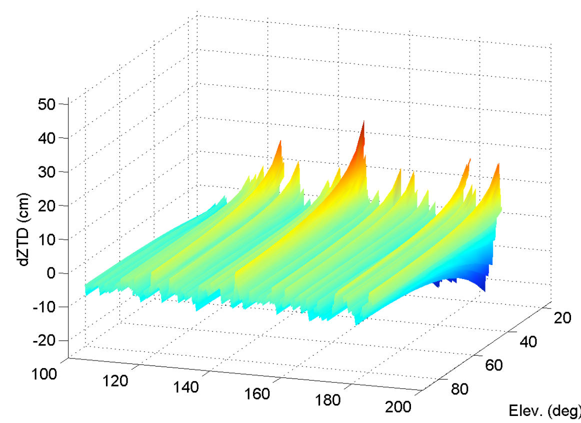

Figure 9: WAAS tropospheric delay estimates mapped to elevation as compared to IGS estimates over ~3 month period for station DWH1 in Washington state.

The Saastamoinen comparison (Figure 10) resembles the NOAA comparison, but the differences from the IGS reference are larger in magnitude.

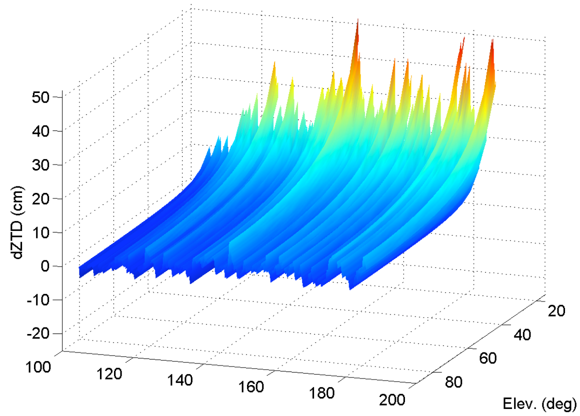

Figure 10: Saastamoinen tropospheric delay estimates mapped to elevation as compared to IGS estimates over ~3 month period for station DWH1 in Washington state.

Figure 11 summarizes all statistics shown for station DWH1. Each row represents the bias, standard deviation, and r.m.s. for the NOAA, WAAS, and Saastamoinen estimates, respectively, as compared again the IGS reference. The three models perform in a similar fashion, with both bias and noise level growing as elevation angle decreases. The only exception to this behavior is the WAAS model bias, what again is being caused by its simple mapping function.

To summaries, total zenith tropospheric delay for ~3 months of 2 hour interval data at station DWH1 were considered. The IGS estimates were used as "truth" and compared against the NOAA, WAAS, Saastamoinen, and Hopfield models. The NOAA comparison values were the smallest, followed by WAAS, then Saastamoinen and Hopfield (which were almost identical, since standard meteorological values were used). This described analysis was expanded to include the almost 20 IGS stations in or near CONUS that produced tropospheric products during the period of study. The results were consistent with those presented for DWH1. Figure 12 illustrates the NOAA zenith total tropospheric delay r.m.s. (as compared to the IGS reference) by geographic region. The r.m.s. values range from approximately 10 to 25 mm.

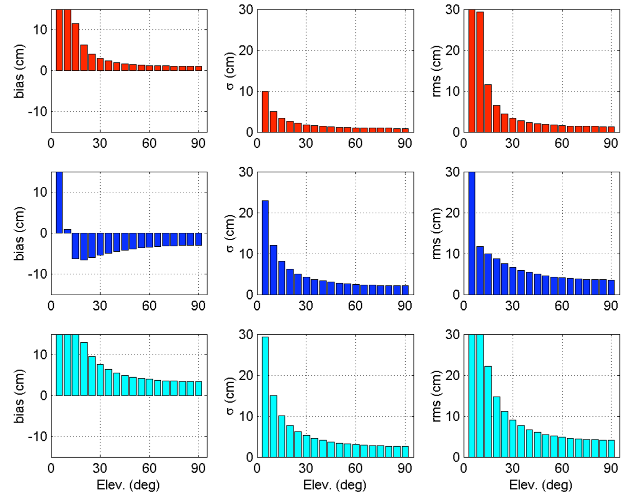

Figure 11: Summary statistics for NOAA (1st row), WAAS (2nd row), and Saastamoinen (3rd row) tropospheric delay estimates as compared to IGS estimates over ~3 month period for station DWH1 in Washington state.

To complete this discuss, two points should be mentioned. One, more data from more stations would be desirable. Ideally, one full year of data encompassing all normal conditions would better justify the use of some of the presented statistics, reference data from the humid southeast would further clarify the performance of NOAA model. Two, it should be noted that GPS data from two of the IGS stations: USNO in the District of Columbia, and AMC2 in Colorado, are assimilated into the NOAA processing [Gutman, 2004]. However, there appears to be no improvement in the predictions at these sites compared to the others. Related, given the density of CORS sites in CONUS, it is more than likely that there are CORS sites near IGS sites that aid in the NOAA delay estimation process, but it is also a fair statement that there are CORS sites in most areas of CONUS economic activity. Also, such a larger amount of processing is performed on the GPS data from collection to output from the NOAA model, that much of the dependencies have been broken.

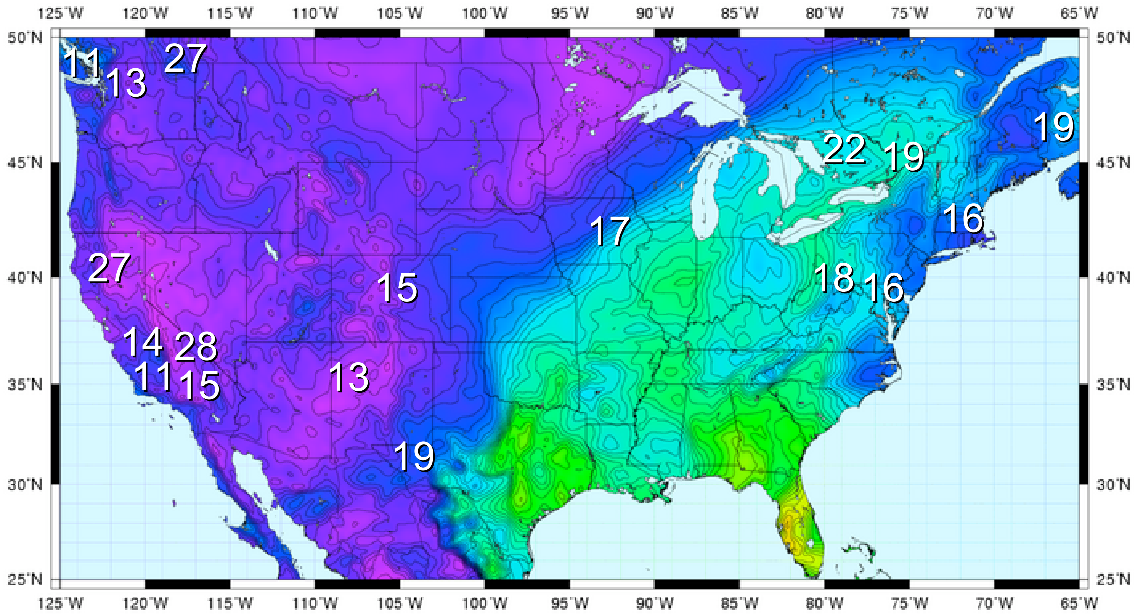

Figure 12: NOAA zenith tropospheric delay estimates r.m.s. (mm) as compared to IGS estimates over ~3 month period for CONUS tropospheric delay estimating IGS stations.

POSITION DOMAIN ANALYSIS

It has been determined in the previous section, based on the data analyzed, that the NOAA zenith tropospheric delay product is 1) a more accurate predictor that the tested closed-form models, and 2) accurate to within 10 to 25 mm when compared against the IGS reference. The next question to tackle is: How does this improved tropospheric delay modeling impact GPS positioning?

To answer this question, we developed in-house relative kinematic positioning software, to simulate Real-Time Kinematics (RTK) firmware in a GPS-based positioning / navigating scenario. The software processes ionosphere-free, double-difference observables to mathematically almost completely eliminate the effects of ionospheric refraction. This combination allows for robust long baseline processing, and removes the ionospheric effect, which otherwise would complicate the analysis, since both atmospheric effects affect GPS positioning in a similar fashion. Also, carrier phase ambiguities were not fixed to integers in the processing, as such an action would introduced biases due to incorrectly fixed terms, and therefore could vastly alter analysis statistics.

At the time of publication, six 24 hour, 30 second interval CONUS-based GPS baseline data sets were processed. Each data set consists of three to five days of observations. The stations selected were CORS sites in the Mid-West, given that they were readily available via the Internet. The use of CORS data will not bias the results, even though CORS GPS measurements are being used in the generation of the NOAA product, since the product itself has been evaluated, and the position domain analysis is designed to evaluate the utility of the product in GPS positioning.

A comparison of positioning results using the Saastamoinen and NOAA tropospheric delay estimates was carried out. Due to its popularity, the Saastamoinen model was selected as the conventional solution.

Figure 13 shows the 1σ r.m.s. (accuracy) in the north, east and up components for the processed data sets as a function baseline length. As expected the errors increase with baseline length, given that the closed-form Saastamoinen tropospheric prediction model is in use. A portion of this baseline error growth (a few centimeters) is due to the use of few-meter-level accuracy broadcast GPS orbits (as this is a real-time simulation). However, as the baselines exceed 200 km, the horizontal errors increase to over 20 cm and the vertical to over 40 cm. These results indicate to there are residual errors in the processing, which will be investigated. We plan to process more baselines from across CONUS to populate the time series, allowing for a more comprehensive characterization of position component accuracy versus baseline length.

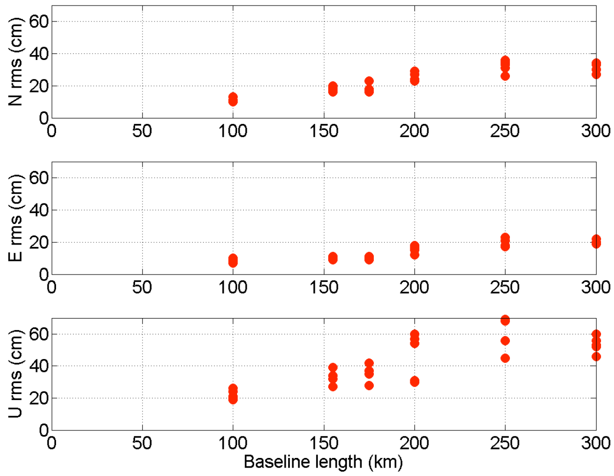

Figure 13: Float ionosphere-free, double-differenced baseline r.m.s. results utilizing the Saastamoinen model.

Figure 14 again illustrates the accuracy versus baseline length relationship, but employing NOAA tropospheric product estimates. Note that the same scale is used as in Figure 13. There is no noticeable change in the horizontal components, but there are reductions in the vertical component errors.

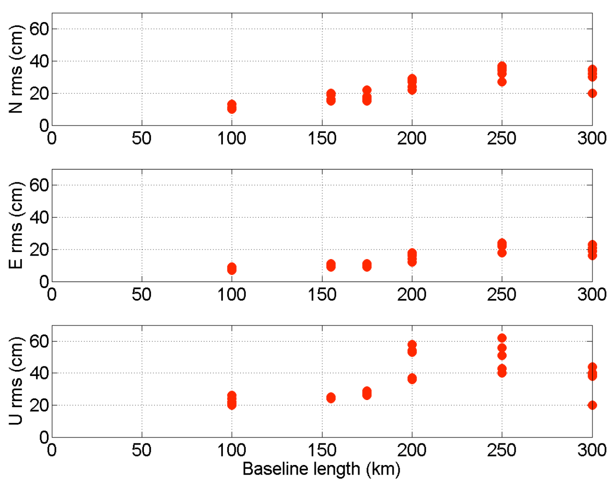

Figure 14: Float ionosphere-free, double-differenced baseline r.m.s. results utilizing the NOAA model.

The improvement in positioning is shown in Figure 15. Clearly there is little or no improvement in the horizontal components – centimeter level, aside from the 300 km data sets. Therefore, more investigation is required for baselines longer than 300 km. There appears to be sizeable r.m.s. improvement in the vertical component, ranging from a few centimeters to over a decimeter. Closer analysis indicates that almost all of the improvement is due to bias reduction.

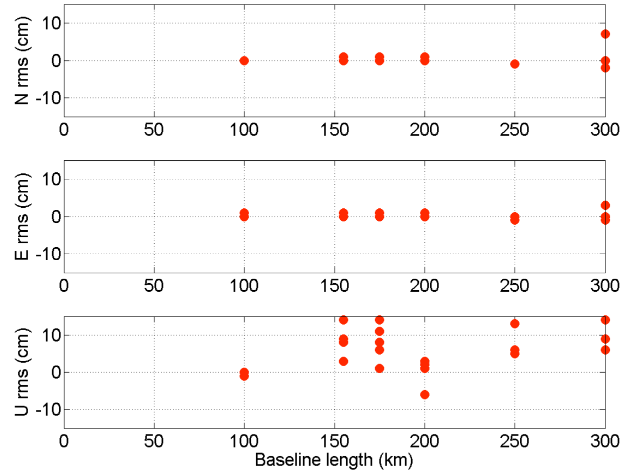

Figure 15: r.m.s. improvement in utilizing the NOAA model over the Saastamoinen model.

The results shown above are similar to those quoted by Alves *et al.* [2004], where NOAA tropospheric data were incorporated into single and multi-baseline processing. A significantly larger data set has been presented in the current work; however, more processing is required to better quantify the improvements. One aspect not discussed, which is a component of further analysis is the height differential between stations. Such differences are not observed in baseline length time series and must be considered.

CONCLUSIONS AND FUTURE RESEARCH

An evaluation of the recently developed NOAA zenith tropospheric delay product has been carried-out. It has been shown how the zenith delay has a very complex spatiotemporal decorrelation. When compared to IGS zenith delay estimates over a three-month period for approximately 20 stations distributed over CONUS, the r.m.s. (i.e., 1σ accuracy) of the NOAA product is on the order to 10 to 25 mm. And the NOAA prediction is consistently closer to the IGS estimates than conventional closed-form prediction models, such as WAAS, Saastamoinen, and Hopfield. When applied to float, ionosphere-free, double-differenced GPS processing, the NOAA predictions show height bias reductions of a few centimeters to over one decimeter on baselines ranging from 100 to 300 km.

Additional research that is required includes more data processing in the range domain analysis. This expansion would include more reference stations, and one year of data from all stations, in order to better characterize

NOAA model performance. In the position domain analysis improvement and expansion of the float processing is needed. Once the float ambiguity analysis is complete, high-quality fixed L1 and L2 ambiguity processing should be attempted. Residual tropospheric estimation should also be introduced to determine if the application of a tropospheric scale factor provides similar results as applying the NOAA tropospheric product. A study of filter convergence should also be complete. Finally, a detailed plan to supply and use the NOAA corrections in the DGPS framework should be proposed

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